

## Recent $CP$ violation results from Belle

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We summarize recent results on an array of  $CP$  violation measurements performed by the Belle experiment using the data collected near the  $\Upsilon(4S)$  and  $\Upsilon(5S)$  resonances at the KEKB asymmetric-energy  $e^+e^-$  collider.

### 1 Introduction

Flavor sector is the largest contributor in terms of number of free parameters to the standard model (SM) of elementary particles – a confluence of electroweak interactions and quantum chromodynamics. In particular, the phenomenon of quark-flavor mixing is described by three Euler angles and one irreducible phase of the so-called Cabibbo-Kobayashi-Maskawa (CKM) matrix<sup>1</sup>. This phase is the lone source of  $CP$  violation within the SM. Unitarity of the  $3 \times 3$  CKM matrix leads to a set of relations among its different elements that can be represented as triangles in the complex plane. One such triangle, better known as the unitarity triangle (UT), is the pictorial sketch of the condition  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ . The raison d'être of the two  $B$ -factory experiments, Belle<sup>2</sup> at KEK and BaBar<sup>3</sup> at SLAC, has been to precisely measure the sides and angles ( $\phi_1$ ,  $\phi_2$  and  $\phi_3$ )<sup>a</sup> of the UT. The underlying idea is to check the overall consistency of the CKM framework; any significant discrepancy between various measurements

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<sup>a</sup>Another notation of  $\beta$ ,  $\alpha$  and  $\gamma$  is also available in the literature.

could be interpreted as potential new physics effects. In these proceedings, we report on recent  $CP$  violation measurements carried out with Belle using  $e^+e^-$  collision data collected near the  $\Upsilon(4S)$  and  $\Upsilon(5S)$  resonances.

## 2 Detector and data

Belle is a large-solid-angle magnetic spectrometer that operated at the KEKB asymmetric-energy  $e^+e^-$  collider. Before stopping the operation in June 2010 to make way for its approved upgrade, Belle II<sup>4</sup>, the experiment has succeeded in accumulating a large data sample spread over various bottomonium resonances – it in fact holds the current world record for the  $\Upsilon(2S)$ ,  $\Upsilon(4S)$  and  $\Upsilon(5S)$  samples. Unless stated otherwise, results presented here comprise the full  $\Upsilon(4S)$  [ $711 \text{ fb}^{-1}$  corresponding to  $772 \times 10^6 B\bar{B}$  pairs] and  $\Upsilon(5S)$  [ $121 \text{ fb}^{-1}$ ] data collected with Belle.

## 3 Methodology

The UT angles  $\phi_1$  and  $\phi_2$  are determined through the measurement of time-dependent  $CP$  asymmetry,

$$A_{CP}(\Delta t) = \frac{N[\bar{B}^0(\Delta t) \rightarrow f_{CP}] - N[B^0(\Delta t) \rightarrow f_{CP}]}{N[\bar{B}^0(\Delta t) \rightarrow f_{CP}] + N[B^0(\Delta t) \rightarrow f_{CP}]}, \quad (1)$$

where  $N[\bar{B}^0/B^0(\Delta t) \rightarrow f_{CP}]$  is the number of  $\bar{B}^0/B^0$ s that decay into a  $CP$  eigenstate  $f_{CP}$  after a proper-time interval  $\Delta t$ , starting with the decay of the other  $B$  in the event ( $B_{\text{tag}}$ ). The  $B_{\text{tag}}$  daughters identify its flavor at the decay time. The asymmetry, in general, can be expressed as a sum of two terms:

$$A_{CP}(\Delta t) = S_f \sin(\Delta m \Delta t) + A_f \cos(\Delta m \Delta t), \quad (2)$$

where  $\Delta m$  is the  $B^0\bar{B}^0$  mixing frequency. The sine coefficient  $S_f$  is related to the UT angles, while the cosine coefficient  $A_f$  is a measure of direct  $CP$  violation. For the  $A_f$  to have a nonzero value, we need at least two competing amplitudes with different weak and strong phases to contribute to the decay final state. The measurement of the UT angle  $\phi_3$  mostly inherits from the nonzero direct  $CP$  violation in some charged  $B$  meson decays.

## 4 $\sin(2\phi_1)$ in $B^0 \rightarrow (c\bar{c})K^0$ decays

The most precise determination of the angle  $\phi_1$  is provided by the  $B^0 \rightarrow (c\bar{c})K^0$  decays. These decays, known as “golden modes”, mainly proceed via the Cabibbo-favored tree diagram  $b \rightarrow c\bar{c}s$  with an internal  $W$  boson emission. The subleading penguin (loop) contribution to the final state, which has a different weak phase compared to the tree-level transition, is suppressed by almost two orders of magnitude. This makes  $A_f = 0$  in Eq. 2 to a very good approximation. Besides very small theoretical uncertainty involved, these channels also offer experimental advantages because of the relatively large branching fractions ( $\sim 10^{-3}$ ) and the presence of narrow resonances in the final state, which provides a powerful discrimination against the combinatorial background.

Belle has updated its previous results<sup>5</sup> on  $\sin(2\phi_1)$  with the entire  $\Upsilon(4S)$  data set. In addition to more data, an improved track reconstruction algorithm has yielded significant enhancement in the reconstruction efficiency, e.g., about 18% improvement in the  $B^0 \rightarrow J/\psi K_S^0$  channel. The  $CP$  eigenstates considered in the analysis are  $J/\psi K_S^0$ ,  $\psi(2S)K_S^0$ ,  $\chi_{c0}K_S^0$  (all  $CP$  odd), and  $J/\psi K_L^0$  ( $CP$  even). Figure 1 shows  $\Delta t$  distributions and time-dependent  $CP$  asymmetries for the candidate events that satisfy good tag quality. The observed asymmetry pattern is consistent with the  $CP$  eigenvalue, and there is a negligible height difference – a measure of direct  $CP$

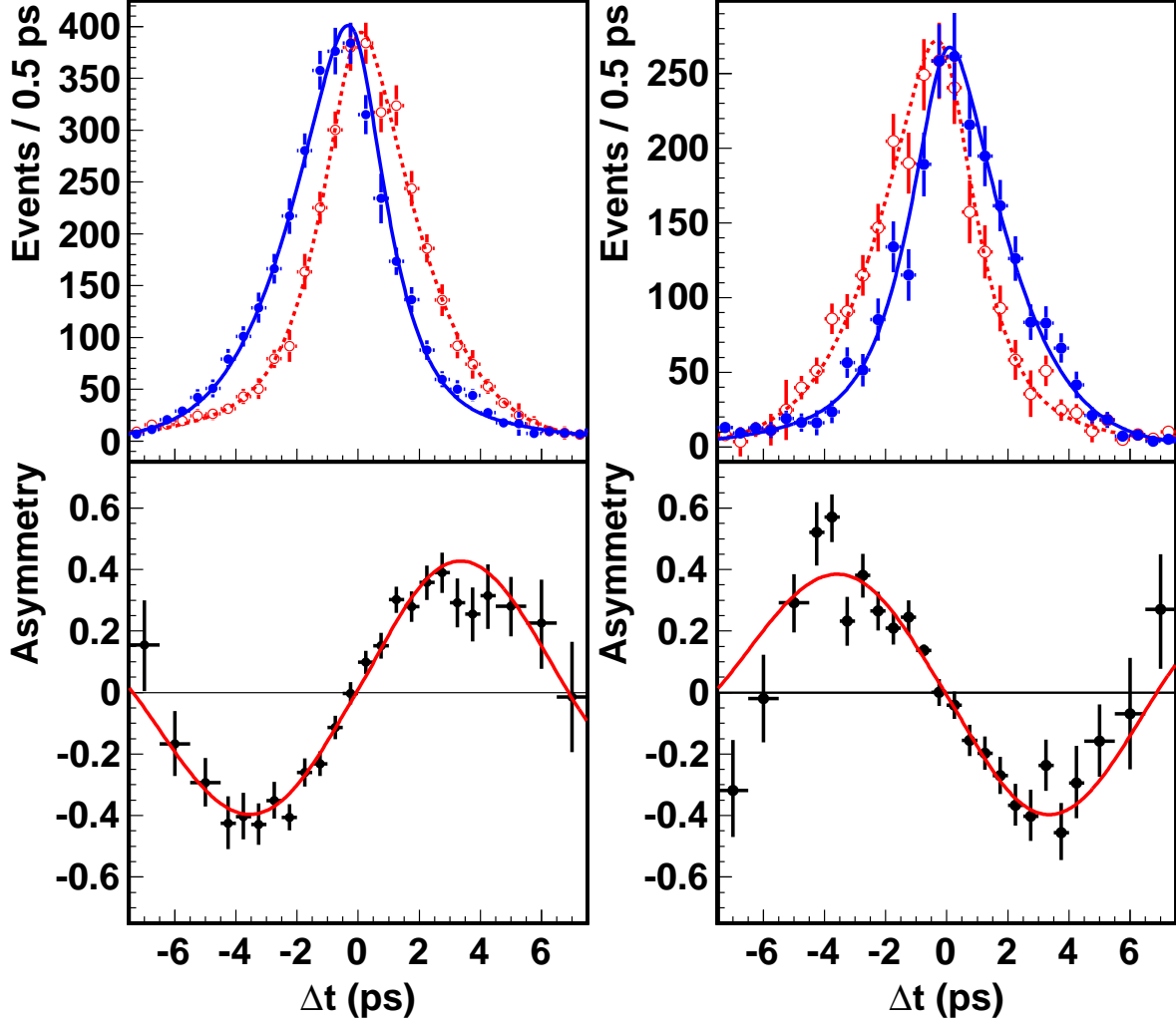


Figure 1: Background-subtracted proper-time distributions (top) for  $\bar{B}^0$  (blue solid) and  $B^0$  (red dotted) tagged events and  $CP$  asymmetry (bottom) for good tag quality events for all considered  $CP$ -odd modes combined (left) and the  $CP$ -even mode (right).

violation – between  $B^0$  and  $\bar{B}^0$  decays. We measure  $\sin(2\phi_1) = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$  and  $A_f = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$ <sup>6</sup>. This constitutes the most precise determination of mixing-induced  $CP$  violation in a  $B$  meson decay, and hence provides a solid reference point for the SM that can be used to test for evidence of new physics.

## 5 $\sin(2\phi_1)$ with the $\Upsilon(5S)$ data

Belle has measured the  $CP$ -violation parameter  $\sin(2\phi_1)$  using a new method called the “ $B$ - $\pi$  tagging”, where the charge of the pion in  $\Upsilon(5S) \rightarrow \bar{B}^{(*)0} B^{(*)+} \pi^-$  decays determines the flavor of the accompanying neutral  $B$  meson. The neutral  $B$  is fully reconstructed in some  $CP$ -specific final state, and there is no need to explicitly reconstruct the charged  $B$  meson. Rather, it can be indirectly inferred through the recoil (missing) mass of the neutral  $B$  and the pion, thanks to the precise knowledge of the energy and momentum of initial states in an  $e^+e^-$   $B$ -factory. One can then extract  $\sin(2\phi_1)$  from the time-integrated asymmetry of the  $\pi^+$  and  $\pi^-$  tagged events:

$$A_{BB\pi} = \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} = \frac{Sx + A}{1 + x^2} \quad (3)$$

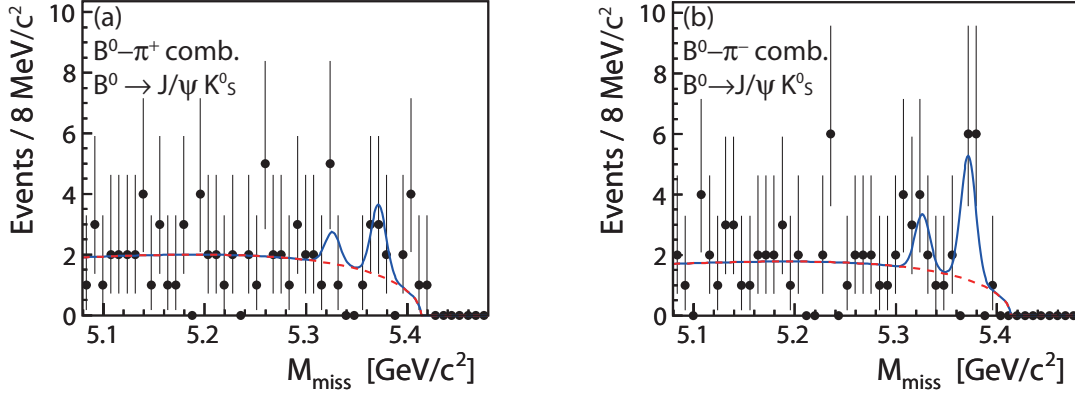


Figure 2: Missing mass distributions for  $B^0 \rightarrow J/\psi K_S^0$  candidates tagged by (a)  $\pi^+$  and (b)  $\pi^-$  in the  $\Upsilon(5S)$  data sample. Points with error bars are the data, solid curves are the fit projections for signal-plus-background, and dashed curves show the background contribution.

where  $S$  ( $A$ ) is the mixing-induced (direct)  $CP$  violation parameter,  $x = (m_H - m_L)/\Gamma$  is the mixing parameter with  $m_H$  ( $m_L$ ) is the mass of the heavy (light) neutral  $B$  mass eigenstate and  $\Gamma$  is their average decay width.

Figure 2 shows the missing mass distributions of neutral  $B$  mesons reconstructed in the channel  $B^0 \rightarrow J/\psi K_S^0$  together with the charged pion, separately for the  $\pi^+$  and  $\pi^-$  tagged samples. Two peaks denote  $B\bar{B}^*\pi + B^*\bar{B}\pi$  (first) and  $B^*\bar{B}^*\pi$  (second) contributions. Expectedly, they are separated by the mass difference between a  $B^*$  and a  $B$  meson. The fit to the available  $\Upsilon(5S)$  sample yields the number of  $\pi^+$  ( $\pi^-$ ) tagged events to be  $7.8 \pm 3.9$  ( $13.7 \pm 5.3$ ); from this we determine  $A_{BB\pi} = 0.28 \pm 0.28(\text{stat})$ . Assuming direct  $CP$  violation term  $A$  to be zero (consistent with the  $B^0 \rightarrow (c\bar{c})K^0$  results) and using the world-average value<sup>7</sup> of the mixing parameter  $x$  ( $0.771 \pm 0.007$ ) in Eq. 3, we obtain  $\sin(2\phi_1) = 0.57 \pm 0.58(\text{stat}) \pm 0.06(\text{syst})$ <sup>8</sup>.

The  $B$ - $\pi$  tagging method is complimentary to the time-dependent analyses carried out at the  $\Upsilon(4S)$  peak with the flavor tagging of neutral  $B$  mesons. Although at the moment we are limited by the available  $\Upsilon(5S)$  statistics, this has a great potential for the super flavor factory experiments such as Belle II.

## 6 Measurement of the angle $\phi_3$

The UT angle  $\phi_3$  unlike  $\phi_1$  (discussed in Section 4) relies on the measurement of direct  $CP$  violation in  $B^- \rightarrow D^{(*)}K^-$  decays caused by interference between the two contributing amplitudes, where both  $D^0$  and  $\bar{D}^0$  mesons decay to a common final state. The fact that one of the amplitudes is almost an order of magnitude smaller than the other ( $B^- \rightarrow \bar{D}^0 K^-$  and  $B^- \rightarrow D^0 K^-$ , respectively) make our life difficult on extracting  $\phi_3$ . The measurements are performed in three different ways: (a) by utilizing decays of  $D$  mesons to  $CP$  eigenstates, such as  $\pi^+\pi^-$ ,  $K^+K^-$  ( $CP$  even) or  $K_S^0\pi^0$ ,  $\phi K_S^0$  ( $CP$  odd)<sup>9</sup>, (b) by making use of doubly Cabibbo suppressed decays of  $D$  mesons, e.g.,  $D^0 \rightarrow K^+\pi^-$ <sup>10</sup>, or (c) by exploiting the interference pattern in the Dalitz plot (DP) of the  $D$  decays such as  $D \rightarrow K_S^0\pi^+\pi^-$ <sup>11</sup>. The first two methods are theoretically clean but suffer from low statistics. The Dalitz method at present provides the strongest constraint on  $\phi_3$ . In the following two subsections, we describe recent updates on  $\phi_3$  from Belle.

Table 1: Results on the  $x, y$  parameters and their statistical correlation for  $B \rightarrow DK$  decays. The quoted uncertainties are statistical, systematic and precision on  $c_i, s_i$ , respectively.

Parameter	$B^\pm \rightarrow DK^\pm$
$x_-$	$+0.095 \pm 0.045 \pm 0.014 \pm 0.010$
$y_-$	$+0.137^{+0.053}_{-0.057} \pm 0.015 \pm 0.023$
$\text{corr}(x_-, y_-)$	$-0.315$
$x_+$	$-0.110 \pm 0.043 \pm 0.014 \pm 0.007$
$y_+$	$-0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.017$
$\text{corr}(x_+, y_+)$	$+0.059$

### 6.1 Model-independent Dalitz plot analysis

Using a model-dependent DP method, Belle's earlier measurement<sup>12</sup> based on a data sample of  $605 \text{ fb}^{-1}$  integrated luminosity yielded  $\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$  and  $r_B = 0.160^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$ , where the uncertainties are statistical, experimental systematic and DP model dependence, respectively. ( $r_B$  is the ratio of the amplitudes for  $B^- \rightarrow \bar{D}^0 K^-$  and  $B^- \rightarrow D^0 K^-$ .) Although with more data one can squeeze on the statistical part, the result will still remain limited by the model uncertainty.

In a bid to circumvent this problem, Belle has carried out a model-independent analysis, following the idea originally proposed by Giri *et al.*<sup>11</sup> that is further extended in a latter work<sup>13</sup>. The analysis is based on the full  $\Upsilon(4S)$  data sample. In contrast to the conventional DP method, where the  $D \rightarrow K_s^0 \pi^+ \pi^-$  amplitudes are parameterized as a coherent sum of several quasi-two-body amplitudes as well as a nonresonant term, the model-independent approach invokes study of a binned DP. In this approach, the expected number of events in the  $i^{\text{th}}$  bin of the DP for the  $D$  mesons from  $B^\pm \rightarrow DK^\pm$  is given by

$$N_i^\pm = h_B [K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i)], \quad (4)$$

where  $h_B$  is the overall normalization and  $K_i$  is the number of events in the  $i^{\text{th}}$  DP bin of the flavor-tagged (whether  $D^0$  or  $\bar{D}^0$ )  $D \rightarrow K_s^0 \pi^+ \pi^-$  decays, accessible via the charge of the slow pion in  $D^{\pm*} \rightarrow D\pi^\pm$ . The terms  $c_i = \langle \cos \Delta\delta_D \rangle$  and  $s_i = \langle \sin \Delta\delta_D \rangle$  contain information about the strong-phase difference between the symmetric DP points  $[m^2(K_s^0 \pi^+), m^2(K_s^0 \pi^-)]$  and  $[m^2(K_s^0 \pi^-), m^2(K_s^0 \pi^+)]$ ; they are the external inputs obtained from quantum correlated  $D^0 \bar{D}^0$  decays at the  $\psi(3770)$  resonance in CLEO<sup>14</sup>. Finally  $x_\pm = r_B \cos(\delta_B \pm \phi_3)$  and  $y_\pm = r_B \sin(\delta_B \pm \phi_3)$ , where  $\delta_B$  is the strong-phase difference  $B^- \rightarrow \bar{D}^0 K^-$  and  $B^- \rightarrow D^0 K^-$ .

We perform a combined likelihood fit<sup>15</sup> to four signal selection variables in all DP bins for the  $B^\pm \rightarrow DK^\pm$  signal and Cabibbo-favored  $B^\pm \rightarrow D\pi^\pm$  control samples; the free parameters of the fit are  $x_\pm, y_\pm$ , overall normalization (see Eq. 4) and background fraction. Table 1 summarizes the results obtained for  $B^\pm \rightarrow DK^\pm$ . From these results we obtain  $\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$  and  $r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$ , where the first error is statistical, the second is systematic, and the last error is due to limited precision on  $c_i$  and  $s_i$ . Although  $\phi_3$  has a mirror solution at  $\phi_3 + 180^\circ$ , we retain the value consistent with  $0^\circ < \phi_3 < 180^\circ$ . We report evidence for direct  $CP$  violation, the fact that  $\phi_3$  is nonzero, at the 2.7 standard deviation ( $\sigma$ ) level. Compared to results of the model-dependent DP method<sup>12</sup>, this measurement has somewhat poorer statistical precision owing to two factors: (a) the error itself is inversely proportional to  $r_B$ , the central value of which has gotten smaller in this analysis and (b) the binned approach is expected to have on average 10–20% poorer result than the unbinned one<sup>13</sup>. On the positive side, however, the large model uncertainty for the model-dependent study ( $8.9^\circ$ ) is now replaced by a purely statistical uncertainty due to limited size of the  $\psi(3770)$  data sample available at CLEO ( $4.3^\circ$ ).

The model-independent approach therefore offers an ideal avenue for Belle II and LHCb<sup>16</sup> in their pursuits of  $\phi_3$ .

## 6.2 GLW and ADS methods

The first two methods proposed for the measurement of  $\phi_3$  (Section 6) also go by the first initials of the authors name: (a) “GLW” for Gronau-London-Wyler<sup>9</sup> and (b) ADS for Atwood-Dunietz-Soni<sup>10</sup>. Although these methods are not as competitive as the Dalitz method, they provide useful complementarity to the final constraint on  $\phi_3$ . For the GLW method, Belle has performed an analysis of  $B^\pm \rightarrow DK^\pm$  using channels in which the neutral  $D$  meson decays to the  $CP$ -even ( $K^+K^-$  and  $\pi^+\pi^-$ ) and  $CP$ -odd [ $K_S^0\pi^0$ ,  $K_S^0\omega(\rightarrow \pi^+\pi^-\pi^0)$ ,  $K_S^0\eta(\rightarrow \gamma\gamma$  and  $\pi^+\pi^-\pi^0)$  and  $K_S^0\eta'(\rightarrow \eta\pi^+\pi^-$  and  $\rho^0\gamma)$ ] states. The physics observables are

$$\begin{aligned} R_{CP\pm} &= 2 \frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D_{\text{fav}}K^-) + \Gamma(B^+ \rightarrow D_{\text{fav}}K^+)}, \\ A_{CP\pm} &= \frac{\Gamma(B^- \rightarrow D_{CP\pm}K^-) - \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}{\Gamma(B^- \rightarrow D_{CP\pm}K^-) + \Gamma(B^+ \rightarrow D_{CP\pm}K^+)}, \end{aligned} \quad (5)$$

where  $D_{\text{fav}}$  denotes the Cabibbo-favored decay mode for the  $D$  meson such as  $D^0 \rightarrow K^-\pi^+$ . These four observables are functions of  $\phi_3$ ,  $r_B$  and  $\delta_B$ . Using the full  $\Upsilon(4S)$  data sample, we obtain  $R_{CP+} = 1.03 \pm 0.07 \pm 0.03$ ,  $R_{CP-} = 1.13 \pm 0.09 \pm 0.05$ ,  $A_{CP+} = +0.29 \pm 0.06 \pm 0.02$ , and  $A_{CP-} = -0.12 \pm 0.06 \pm 0.01$ , where the quoted errors are statistical and systematic, respectively. There is clear evidence of direct  $CP$  violation ( $A_{CP} \neq 0$ ) for the  $CP$ -even modes. In the case of ADS method our study extends to  $B^- \rightarrow D^*K^-$ ,  $D^* \rightarrow D\gamma(D\pi^0)$  where the  $D$  meson is reconstructed in the doubly Cabibbo suppressed channel  $D \rightarrow K^+\pi^-$ . We report the first evidence for signal in this mode with a  $3.5\sigma$  significance.

## 7 Study of $B \rightarrow \eta h$ ( $h = K, \pi$ ) decays

The  $B^\pm \rightarrow \eta^{(\prime)}h^\pm$  ( $h = K, \pi$ ) decays proceed via  $b \rightarrow s$  penguin processes and Cabibbo-suppressed  $b \rightarrow u$  tree transition, as shown in Fig. 3. The large  $B \rightarrow \eta'K$  and small  $B \rightarrow \eta K$  branching fractions can be thought of as an artifact of  $\eta - \eta'$  mixing together with the constructive and destructive interference between the two penguin diagrams. On the other hand, owing to small contribution from the color-suppressed tree in case of  $B^0 \rightarrow \eta K^0$ , its branching fraction is expected to be lower than that of  $B^+ \rightarrow \eta K^+$ . Concerning direct  $CP$  violation, one could find sizeable effects in  $B^\pm \rightarrow \eta h^\pm$ , proportional to the degree of interference between the contributing penguin and tree amplitudes.

Using the entire  $\Upsilon(4S)$  data sample of Belle, we have studied  $B \rightarrow \eta h$  decays<sup>17</sup> where the  $\eta$  meson is reconstructed in the two channels  $\eta \rightarrow \gamma\gamma$  and  $\eta \rightarrow \pi^+\pi^-\pi^0$ . The measured branching fractions are  $\mathcal{B}(B^\pm \rightarrow \eta K^\pm) = [2.12 \pm 0.23(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-6}$ ,  $\mathcal{B}(B^\pm \rightarrow \eta \pi^\pm) = [4.07 \pm 0.26(\text{stat}) \pm 0.21(\text{syst})] \times 10^{-6}$  and  $\mathcal{B}(B^0 \rightarrow \eta K^0) = [1.27^{+0.33}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})] \times 10^{-6}$ . The dominant systematic errors are due to uncertainties on reconstruction efficiencies of the  $\eta$ ,  $\pi^0$  and  $K_S^0$  mesons. The  $B^0 \rightarrow \eta K^0$  decay is observed for the first time with a significance of  $5.4\sigma$ . We also find evidence for  $CP$  violation in the charged  $B$  decay channels,  $A_{CP}(B^\pm \rightarrow \eta K^\pm) = -0.38 \pm 0.11(\text{stat}) \pm 0.01(\text{syst})$  and  $A_{CP}(B^\pm \rightarrow \eta \pi^\pm) = -0.19 \pm 0.06(\text{stat}) \pm 0.01(\text{syst})$  with significances of  $3.8\sigma$  and  $3.0\sigma$ , respectively. All these branching fraction and  $CP$  measurements supersede our earlier results<sup>18</sup>.

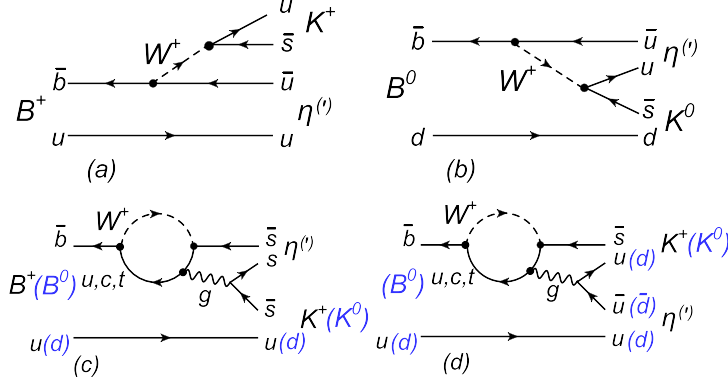


Figure 3: (a)  $b \rightarrow u$  tree diagram for  $B^+ \rightarrow \eta^{(\prime)} K^+$ , (b) color-suppressed  $b \rightarrow u$  tree diagram for  $B^0 \rightarrow \eta^{(\prime)} K^0$ , and (c),(d)  $b \rightarrow s$  penguin diagrams for  $B \rightarrow \eta^{(\prime)} K$ .

## 8 Conclusions and future prospect

Among the sample of results we presented at this prestigious conference of Moriond include the most precise determination of  $\sin(2\phi_1)$  in the  $B \rightarrow (c\bar{c})K^0$  decays, a novel method to determine the same parameter in the  $\Upsilon(5S)$  data, a first model-independent DP analysis to determine the UT angle  $\phi_3$ , and evidence for direct  $CP$  violation in  $B \rightarrow \eta h$ . The second and third measurements are more of a proof-of-principle in nature, and hold a great promise for experiments at the super flavor factories. At the moment, there are many ongoing  $CP$  related analyzes, such as the UT angle  $\phi_2$ , with the full  $\Upsilon(4S)$  statistics of Belle. Therefore we expect many interesting results to come out soon while one is waiting for the next phase of the experiment, Belle II.

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